N89-20077

EVALUATION OF CRUSTAL RECYCLING DURING THE EVOLUTION OF ARCHEAN-AGE MATACHEWAN BASALTIC MAGMAS

Final Report

NASA/JSC Summer Faculty Fellowship Program--1988

Johnson Space Center

Prepared By: Dennis O. Nelson, Ph.D.

Academic Rank: Professor

University & Department: Sul Ross State University
Geology Department
Alpine, Texas 79832

NASA/JSC

Directorate: Space and Life Sciences

Division: Solar System Exploration

Branch: Planetary Science

JSC Colleague: Donald A. Morrison, Ph.D.

Date Submitted: August 12, 1988

Contract Number: NGT 44-005-803

ABSTRACT

The Matachewan-Hearst Dike swarm consists of plagioclase megacryst-bearing tholeiite dikes that were emplaced over an area of approximately 250,000 km2 of the Superior Province near the end of the Archean (2.45 Ga). Invaded supracrustal rocks vary from metavolcanic dominated granitoid-greenstone belts to subprovinces dominated by metasedimentary lithologies. The dike compositions vary from depleted ($[La/Sm]_n < 0.8$) to moderately enriched ($[La/Sm]_n > 1.80$) and define linear arrays in compositional space (data can be obtained from the author). Neither the composition of the immediate country rock nor the individual subprovince in which a given dike is located exerts significant control on dike composition. Although variations in individual element concentrations were produced by shallow combined replenishment-fractional crystallization (RFC), the range in incompatible element ratios, e.g. $[La/Sm]_n$, insensitive to RFC, requires additional processes. Relative abundances of the rare earth (REE) and high field strength (HFSE) elements suggest either crustal contamination or involvement of a slab-derived component. Distinguishing between these two alternatives is important in determining whether or not crustal formation/evolution at the end of the Archean was by subduction-related processes or some alternative such as underplating. Combined assimilation-fractional crystallization (AFC) models, using crustal rock data from xenoliths and from the adjacent Kapuskasing Structural Zone (KSZ) in which lower crustal rocks are exposed, suggest that assimilation can accommodate the incompatible element variation. The assimilant was dominated by silicic granitoids (tonalite to granodiorite) although mixing of parental dike magmas with partial melts of previously underplated basaltic rocks best explains some dikes. Assimilation rate, expressed as mass of assimilant to mass of cumulate phases, was approximately 0.5; total relative mass assimilated varied from 5 to 20 percent. Although the Matachewan-Hearst magmas possessed compositional signatures often attributed to a slab-derived component, e.g. high REE/HFSE, $Ta/Ta^* = 0.17-0.41$ and falling within the 'destructive plate margin' field on a Th-Hf-Ta diagram, modeling indicates that these characteristics can be produced by AFC involving observed depleted dike compositions and granitoids of the KSZ. Partial melt models of a hypothetical amphibole-bearing peridotite (slab-component enriched [?]) produce variations in Ti/Ti^* and $(Tb/Yb)_n$ that are not compatible with the MD data. AFC processes during underplating of the existing Archean crust produced the variations in incompatible element ratios, including the relative depletions of the HFSE.

ORIGINAL PAGE IS OF POOR QUALITY

INTRODUCTION

Basaltic magma, derived through the partial melting of planetary mantles, is a fundamental product of all the terrestrial planets (1). The ascent of basalt magma is one of the principal mechanisms of transfering 'juvenile' mantle material to the surface. Subsequent chemical differentiation of basaltic magma in that environment is important in the generation of new crust and the modification of pre-existing crust. Data from missions to the other terrestrial planets (i.e. Mercury, Venus, Moon and Mars) suggests that all of these bodies have undergone differentiation into crust and mantle domains to varying extents; Earth and Moon are endmembers representing the greatest and least extents of this differentiation. Although there is broad agreement that the Earth's crust formed through chemical processing of the mantle and its derivatives, the mechanism(s) by which this was accomplished is(are) a matter of debate (2, 3). Although estimates vary, it is clear that the bulk of the Earth's crust formed prior to the Late Archean (2.5 billion years ago (Ga)) (3). Of interest is whether crustal growth and evolution during the Late Archean occurred in a manner similar to more modern environments, (e.g. involving lateral plate motions and in particular, subduction processes), or was early crustal genesis dominated by vertical tectonics, involving the process of underplating (e.g. 4). In the latter process, large volumes of basalt magma pool at the base of the low-density crust. The subsequent crystallization and differentiation of this magma adds to mass of the crust. Distinguishing between a modern plate tectonic model and the underplating process requires knowledge of the chemical nature of the mantle source (i.e. is it comparable to modern sources of convergent zone magmas) and the extent and nature of crustal recycling (i.e. crustal melting and assimilation) during the underplating process. In this particular study, the major and trace element compositions of dikes from the extensive Matachewan-Hearst swarm are evaluated in order to characterize their mantle source(s) and to identify the process(es) of magmatic differentiation that operated during their evolution.

BACKGROUND

The Matachewan-Hearst dikes (MHD) represent very large-scale basaltic magmatism that occurred in a stable continental mass (5) at 2.45 Ga (6). The dikes exhibit a north to northwestward trend for a strike distance of over 700 km and an areal extent of approximately 250,000 km2.

The large size of the swarm results in the dikes crossing litho-tectonic boundaries along which Archean blocks (i.e. subprovinces) of markedly different lithologic character have been juxtaposed. The subprovinces can be described as metavolcanic-rich belts, e.g. the Abitibi, Wawa and Wabigoon subprovinces, separated by intervening metasedimentary belts such as the Quetico and English River Gneiss belts (7, 8). A northeast-trending structural discontinuity, the Kapuskasing Structural Zone (KSZ), forms a western boundary along the central portion of the swarm and has been interpreted as an oblique cross section through the Archean crust (9). Studies of KSZ rocks indicate that the Archean-age crust is a complex mixture of mafic to silicic rocks that has been metamorphosed to conditions of amphibolite to granulite facies (5, 10, 11). Geochemical studies indicate that the granulitic portion of the Archean crust in the KSZ has not been depleted to the extent of more 'typical' lower crust elsewhere (10, 11).

Most of the MHD host plagioclase megacrysts whose composition (AN85$\pm$5) is identical to the plagioclase in Archean anorthosites of the Superior Province (12, 13). Trace element modeling (14, 15) of a subset of the MHDs suggests that a hierarchy of controls on MHD magma composition occurred. On a local scale, flow differentiation and multiple magma injection produced chemical variability observable within single traverses across dikes. Variations in the concentrations, observed in both intra- and interdike suites, were produced in part by combined replenishment-fractional crystallization (RFC). This process resolves the apparent decoupling of major- and trace element variations (14, 15) and is consistent with the uniform (i.e. non-zoned) plagioclase megacrysts (12). The RFC process, however, is incapable of producing the observed range in values of incompatible element ratios, e.g. (La/Sm)n varies from 0.62 to 2.02. As illustrated in figure 1, the processes of simple fractional crystallization (FC) and RFC, although capable of affecting a significant change in the concentration of a given element, La in this case, are incapable of producing detectable changes in the (La/Sm)n ratio. A pre-RFC stage of evolution, involving other processes, must have operated. Such processes, which are not mutually exclusive, include combined assimilation-fractional crystallization (AFC) and source effects.

In the AFC process, basaltic magma either melts, dissolves or otherwise assimilates crustal material. Energy required for the assimilation is derived from the latent heat of crystallization released as the magma simultaneously crystallizes. The exact trajectory of compositional evolution (e.g. fig. 1) will depend on (a) the composition of the parent magma, (b) the composition of crystallizing phases, (c) the partitioning of elements between the crystallizing phase and the melt, (d) the composition of the assimilant and (e) the rate of assimilation to crystallization. Clearly, the AFC process cannot be described in terms of a simple mix between the parent magma and the contaminant.

Source effects refer to the impact that chemical heterogeneity in the mantle source and/or variations in the melting processes can have on the compositions of the derivative melts. Numerous studies have shown that the mantle is non-uniform, both on a local and regional scale. If different sources are tapped or if a single markedly heterogeneous mantle is variably melted (16), variations in incompatible element ratios can be produced (fig. 1).

GEOCHEMICAL MODELS

The MHD magmas inherited a certain amount of compositional variability, either from the mantle source(s) from which they were derived, from interaction with lower crust through AFC, or from both. In this section, these two alternatives are explored in more detail. Algorithms of the AFC and melting processes generate hypothetical magmatic evolution paths. These calculated trajectories are compared to the actual data to develop and test various geochemical models. In addition, the calculations help constrain models regarding the chemical nature of the lower crust and mantle source(s). This information is pertinent to arguments of whether or not plate tectonics operated prior to the generation of the MHD magmas.

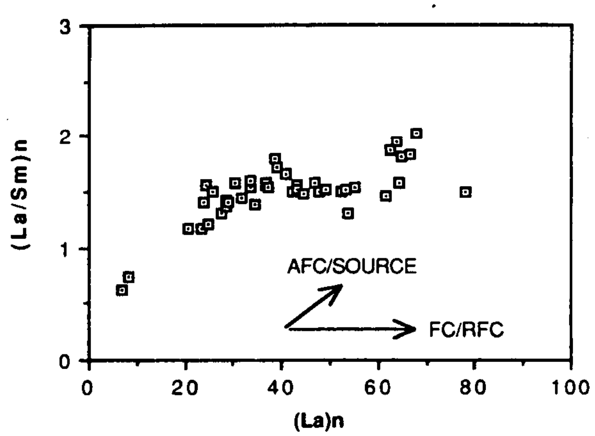

Figure 1.- A plot of chondrite-normalized La against (La/Sm) for the MHD data (squares). Also shown are vectors indicating the direction of compositional evolution via processes discussed in text.

A compositional characteristic of the MHD rocks pertinent to this argument is the relative depletion of the high-field-strength elements (HFSEs), e.g. Ta, Ti, Nb, relative to the rare earth elements (REEs). Values for $(La)_n/Ta$ in the MHD range from <40 to >160. Both La and Ta are incompatible elements in basaltic systems; Such a range would not be expected during FC/RFC or melting processes. Fractionation of La from Ta is believed to be characteristic of magmatic rocks, including more silicic differentiates, produced by subduction zone processes (17, 18).

For this study, data for volcanic rocks from a number of tectonic environments was compiled and compared with the MHD. The fields of oceanic island basalt (OIB), ridge basalts (RB) from modern spreading centers, volcanic rocks erupted on continents either as subduction zone related continental arcs (CA) or as continental flood- and rift basalts (CV), and a single example of an oceanic arc, the Finger Bay center in the Aleutians (FB) are plotted in figure 2. The bulk of the MHD plot within the field of CA/CV, distinct from OIB, FB and RB. It would appear that the source of the MHD magmas was not similar to that of modern oceanic islands. Although the MHD lie within a field that includes subduction zone magmas (CA), crustal contamination is possible in all plotted cases. Further, the MHD data define a linear trend from the RB field towards that of crustal rocks (CR).

Assimilation-Fractional Crystallization

Condie et al. (19) argue that crustal contamination was not important in the evolution of the MHD magmas. This conclusion is based on two assumptions that, on close inspection, do not appear valid. They assume that 1) parental magmas of the MHD were identical to modern MORB, and 2) the lower crust in the Superior Province was depleted in LILE, similar to "uplifted Archean granulite terrains". In fact, the more primitive of the MHD magmas have some significant differences with modern MORB, e.g. a low Zr/Nb ratio (<8.6 in contrast to >20 as assumed by these authors). Further, studies of lower crust exposed in the KSZ clearly indicate that these granulite facies rocks are not depleted in a style typical(?) of other such terrains (10, 11). Also implicit in the qualitative arguments of Condie et al. (19) is that contamination is only a two endmember process. As discussed above, it is not. In this study, AFC models were developed from crustal rock data, e.g. a granodiorite xenolith and tonalitic compositions from the KSZ (10). In addition to considering bulk assimilation of silicic granitoids, models reflecting mixing of basaltic magma with partial melts of basaltic precursors ($\pm$

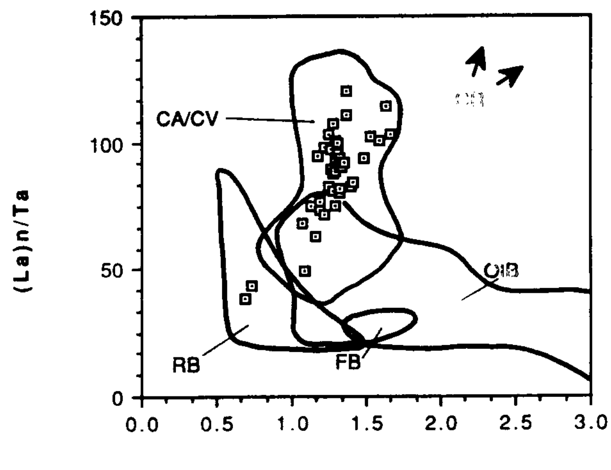

Figure 2.- A discriminant diagram, plotting (Ce/Sm)n against (La)n/Ta for rocks from the environments of oceanic islands (OIB), spreading centers (RB), an oceanic arc (FB) and rocks emplaced on the continents, either above subduction zones, as flood basalts or in rift zones (CA/CV). The MHD data shown as squares. Arrows point in the direction of crustal rocks (CR).

garnet in the residuum) are considered. These latter assimilants are considered because of the possibility that underplating is an episodic process (4), and that the partial melting of previously underplated basalts might provide a potential contaminant. Experimental results suggest that the major element compositions of such melts will be tonalitic (20). Remelting of the tonalites (partial melts of earlier underplated basalts[?]) would yield liquids in the granodiorite to granite range (21).

In figure 3, the MHD data are shown as a field on the Th-Hf-Ta triangular diagram of Wood (22). The data fall within the field of "destructive plate-margin basalts and differentiates" (22, p. 12). Menzies et al. (23) point out that magmas assimilating Th-rich crustal rocks will be displaced towards the Th apex of the triangle. AFC calculations in this study substantiate this claim. The symbols in figure 3 represent the trajectories of AFC, assuming a depleted parental magma (symbols in field N) and either silicic or mafic granulites as assimilants. Although the various assimilants can not be discriminated, it is clear that the AFC process can explain the MHD data.

The relative abilities of the four assimilants are evaluated in figure 4. Incompatible element ratios are utilized here to essentially filter out the effect of subsequent RFC processes. RFC will not produce significant variations in these ratios (fig. 1). Figure 4 indicates that the MHD data can best be accommodated by AFC processes involving silicic granitoids. The assimilation rate used

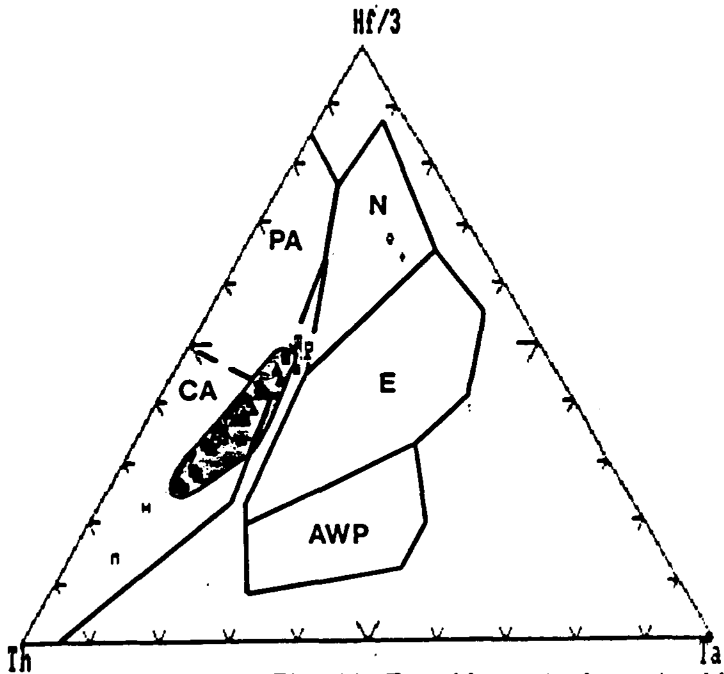

Figure 3.- Triangular Th-Hf-Ta discriminant diagram of Wood (24). Fields are N-type (N) and E-type (E) MORB, alkaline within plate basalts and differentiates (AWP), primitive arc tholeiites (PA) and calc-alkaline basalts and differentiates (CA). MHD data are shown as shaded field and the two points in the N field. Symbols track the trajectories of AFC models.

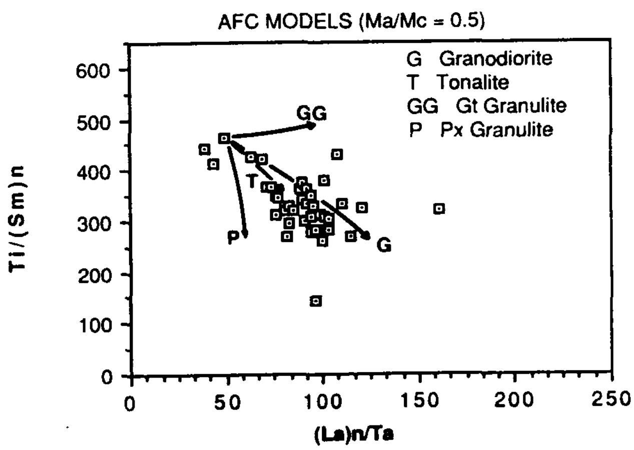

Figure 4.- Plot of (La)n/Ta versus Ti/Sm for MHD data (squares). Vectors represent AFC models (Ma/Mc = 0.5) for various assimilants as labeled.

was 0.5 (= mass of assimilant/mass of cumulates), a rate consistent with conditions of the lower crust. Several factors contribute to the scatter of the MHD data. The MHD data considered in this study occur over an area of 60,000 km2. Given the lithologic diversity of the lower crust (10, 11), and the possibility of variable assimilation rates, one can envision a splay of vectors originating from the parental composition. Heterogeneities within the mantle source are also possible, although isotopic data suggest that variations were small and the mantle was depleted in character (24, 25). The isotopic support for a depleted source is consistent with the choice of the light-REE depleted MHD compositions as parental liquids. In figure 5 the impact of AFC, incorporating small variations in source compositions, has been evaluated. Compositions 18B and 15B represent a MHD and an older pillowed flow rock, respectively; both, therefore, reflect variations in mantle chemistry below the Superior Province. The parameters Ta/Ta* and Ti/Ti* (Ta and Ti anomalies) analogous to Eu anomalies, are calculated from the extended REE diagrams of Briqueu et al. (18). The AFC calculations portrayed in this figure indicate that taking into account minor heterogeneities in both the mantle source and the lower crust will account for the bulk of the MHD data.

Further examination of the models and data of figure 5 indicate that some of the MHD compositions appear to require an assimilant derived from a mafic (i.e. basaltic) precursor. AFC calculations indicate that this mafic source rock must have been light-REE enriched; the use of partial melts of depleted compositions such as 15B and 18B as contaminants were unsuccessful. Figures 4 and 5 also indicate that if the mafic rock had a garnet-free mineralogy, partial melts of this assemblage would be unsuccessful contaminants. The implication of a garnet-bearing residuum is that the crust must have been thick enough to stabilize this phase. The requirement for a mixed silicic-mafic assimilant package emphasizes the heterogeneous nature of the lower crust (5, 9 and 11).

The relative success of the AFC models is illustrated in the extended REE diagram given in figure 6. Shown in this figure is a potential parental composition (15B), a granodiorite contaminant (3G), and an evolved MHD composition (25A). The stippled field is the range of compositions produced through AFC (Ma/Mc = 0.5) after the original magma mass has been reduced by 10 to 20 percent. It is evident that the trace element composition of 25A is consistent with such a process. Condie et al. (19) argued that significant assimilation of silicic crust would change the silica content of the evolved magma to that uncharacteristic of basalt. Recalling that the AFC process involves

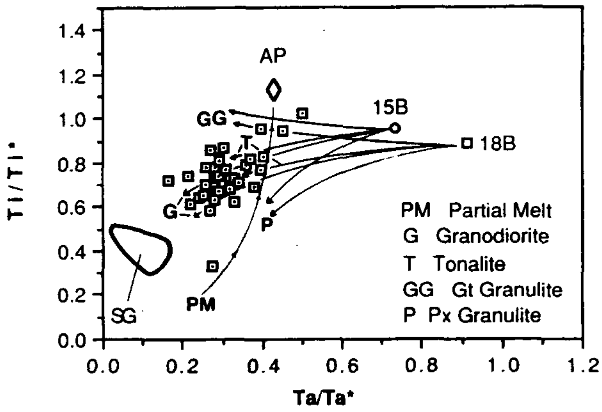

Figure 5.- Anomalies of Ta versus Ti (see text and 20) for MHD data (squares), various AFC models involving possible parental melts 15B and 18B, and partial melt trajectory from a hypothetical metasomatized amphibole-bearing peridotite (AP). Tonalitic compositions (10) from the KSZ shown as outlined area (SG).

three endmembers (parental magma, assimilant and cumulate phases), it is noted that the liquidus assemblage of the MHD magmas must have been dominated by clinopyroxene and plagioclase (14), both of which have silica contents higher than the parental magma. Fractionation of such phases offset the higher silica content (in the case of 3G, approximately 70 percent) of the assimilant. Qualitative calculations indicate that the AFC model portrayed in figure 6 produces an evolved liquid having a SiO_2 content consistent with that of 25A.

Enriched Mantle Source(s)

In the previous section it was demonstrated that AFC processes can produce the compositional characteristics of the MHDs. In this section, the possibility that these characteristics could alternatively reflect an enriched source is evaluated. Of particular interest is whether or not a source, previously enriched by subduction zone processes, is indicated. The depletion of HFSE relative to the LILE and REE, observed in the MHD data, is interpreted by some to be unique to subduction related volcanism (e.g. 18, 27), resulting from the transfer of the LILE and REE from the slab as a result of dewatering processes (17). The fractionation of LILE and REE from the HFSE, however, may

ORIGINAL PAGE IS
OF POOR QUALITY

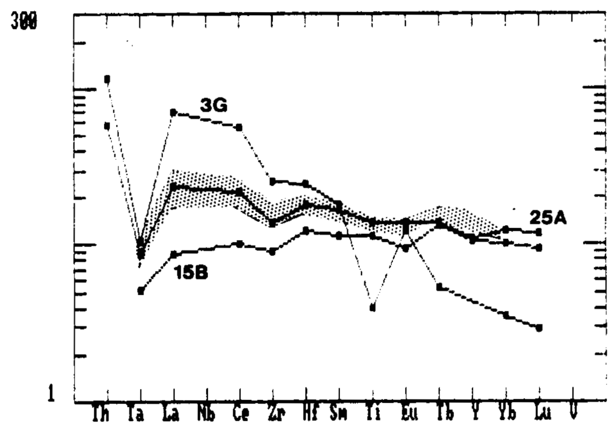

Figure 6.- Extended REE diagram for samples and models of the MHD. All compositions normalized to values given by Briqueu et al. (20). Sample 15B represents a possible parental MHD composition, 3G is a granodiorite xenolith considered as potential crustal contaminant, and 25A is intermediate MHD composition. Stippled area represents range of compositions produced by AFC (Ma/Mc = 0.5; 15B as parent and 3G as contaminant), with F = 0.9 to 0.8.

also be a function of restite mineralogy, in particular Ti-rich phases such as sphene or magnetite (18). Further, Arculus (28) has argued that the LILE enrichment relative to HFSE may not be restricted to subduction zones, but may also occur in continental terrains (see figure 2), being more a function of process than tectonic environment. In agreement, the partial melt calculations discussed above indicate that HFSE anomalies can be produced during the underplating process by the melting of basaltic precursors.

In order to evaluate whether or not the MHD magmas may have been derived through variable melting of mantle, previously enriched above a subduction zone, partial melt calculations were performed on a hypothetical amphibole-bearing peridotite. Metasomatic fluids would likely produce modal amphibole at the expense of clinopyroxene (29). Progressive melting of such a source (Fig. 5) would result in decreases in both Ti and Ta anomalies, with Ti being affected to the greatest extent. Few of the MHD data conform to such a trend. In figure 7a, the ability of amphibole to fractionate middle-REEs (Tb) from heavy-REEs (Yb) is noted. The MHD data clearly do not correspond to the trend of variable melting of an amphibole-bearing peridotite. Rather, the MHD compositions are subparallel to AFC trajectories involving silicic granitoids as contaminants. Finally, we note that a consistent relation exists between (La)n and Ta/Ta* and Ti/Ti* (Fig. 7b). Recall that shallow-level RFC processes affect the (La)n value but would have no impact on anomaly values. If variable melting of an enriched source was responsible for the anomaly values, then, in order to maintain the relationship shown in figure 8b, the shallow RFC would have to be related to the extent of mantle melting, an improbable relationship.

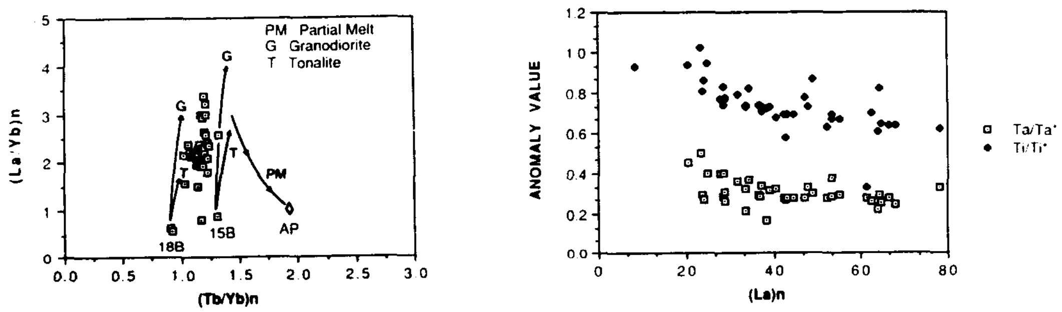

Figure 7.- (a) Plot of (Tb/Yb)n against (La/Yb)n, showing partial melt and AFC trajectories. Symbols as in figure 5. (b) Anomalies of Ta and Ti plotted against (La)n for the MHD data.

CONCLUSIONS

The simplest model for the MHD magmas is AFC, presumably occurring at the base of the crust during underplating. Subduction zone enriched mantle sources are not required. Trace elements suggest that the mantle sources for the MHD were depleted, but possessed a degree of heterogeneity. Rates of assimilation were approximately 0.5 (= Ma/Mc); the contaminant mass was <20%. The contaminant was dominated by tonalites-granodiorites, similar to xenoliths and rocks in the KSZ. Assimilation of partial melts of light-REE and garnet-bearing basaltic precursors may have produced some the MHD magmas. Apparently, previous underplating-AFC processes had already produced a thick crust. The silicic granitoid assimilant for the MHD magmas was probably produced by earlier processing of underplated mafic crust (4, 5, 10, 21 and 30). Calculations suggest that the derived silicic rocks possess negative Ta and Ti anomalies even though they were not the product of subduction.

REFERENCES

1. Basaltic Volcanism Study Project: Basaltic Volcanism on the Terrestrial Planets. Pergamon Press, 1981, 1286 pp.
2. Etheridge, M.A.; Rutland, R.W.R.; and Wyborn, L.A.I.: Orogenesis and Tectonic Process in the Early to Middle Proterozoic of Northern Australia. Proterozoic Lithosphere Evolution, A. Kroner, ed., Am. Geophys. Union Geodynamics Series Volume 17, 1987, pp. 131-148.
3. Allegre, C.J.: Chemical Geodynamics. Tectonophysics, v. 81, 1982, pp. 109-132.
4. Wass, S.Y.; and Hollis, J.D.: Crustal Growth in South-Eastern Australia-Evidence from Lower Crustal Eclogite and Granulitic Xenoliths. J. Metamorphic Geol., v. 1, 1983, pp. 25-45.
5. Percival, J.A.; and Card, K.D.: Structure and Evolution of Archean Crust in Central Superior Province, Canada. Evolution of Archean Supracrustal Sequences, L.D. Ayres, P.C. Thurston, K.D. Card and W. Weber, eds., Geol. Assoc. Canada Spec. Paper 28, 1985, pp. 179-192.
6. Heaman, L.: Geol. Assoc. Canada, Program with Abstracts, v. 13, 1988.
7. Card, K.D.: Geology and Tectonics of the Archean Superior Province, Canadian Shield. LPI Tech. Rept., No. 86-04, 1986, pp. 27-29.
8. Percival, J.A.: Metamorphism and Plutonism in the Quetico Belt, Superior Province, N.W. Ontario. LPI Tech. Rept. No. 86-04, 1986, pp. 84-85.
9. Percival, J.A.; and Card, K.D.: Archean Crust as Revealed in the Kapuskasing Uplift, Superior Province, Canada. Geology, v. 11, 1983, pp. 323-326.
10. Rudnick, R.L.; and Taylor, S.R.: Geochemical Constraints on the Origin of Archaean Tonalitic-Trondhjemitic Rocks and Implications for Lower Crustal Composition. The Nature of the Lower Continental Crust, J.B. Dawson, D.A. Carswell, J. Hall, and K.H. Wedepohl, eds., Geol. Soc. Spec. Pub. 24, 1986, pp. 179-192.
11. Ashwal, L.D.; Morgan, P.; Kelley, S.A.; and Percival, J.A.: Heat Production in an Archean Crustal Profile and Implications for Heat Flow and Mobilization of Heat-Producing Elements. Earth Planet. Sci. Lett., v. 85, 1987, pp. 439-450.
12. Phinney, W.C.; Morrison, D.A.; and Maczuga, D.E.: Anorthosites: An Analogue Study. Lun. Sci. Conf. XVIII, 1987, pp. 774-776.
13. Morrison, D.A.; Phinney, W.C.; and Maczuga, D.E.: Archean Anorthosites: Constraints on the Accumulation Process. Lun. Sci. Conf. XVIII, 1987, pp. 670-671.

14. Nelson, D.O.: Petrogenesis of Basalts from the Archean Matachewan Dike Swarm, Superior Province of Canada. Final Report, NASA/ASEE Sum. Fac. Fellow. Prog., NGT 44-001-800, 1987, pp. 22-1 - 22-20.
15. Nelson, D.O.; Morrison, D.A.; Phinney, W.C.; and Maczuga, D.E.: Geochemistry of Archean Matachewan Dikes of the Superior Province of Canada. EOS, v. 68, 1987, p. 1518.
16. Nelson, D.O.; and Nelson, K.L.: Geochemical Comparison of Alkaline Volcanism in Oceanic and Continental Settings: Clarion Island Versus the Eastern Trans-Pecos Magmatic Province. Mantle Metasomatism and Alkaline Magmatism, E.M. Morris and J.D. Pasteris, eds., Geol. Soc. America Spec. Paper 215, 1987, pp. 317-334.
17. Tarney, J.; Wood, D.A.; Saunders, A.D.; Cann, J.R.; and Varet, J.: Nature of Mantle Heterogeneity in the North Atlantic: Evidence from Deep Sea Drilling. Phil. Trans. R. Soc. Lond. A 297, 1980, pp. 179-202.
18. Briqueu, L.; Bougault, H.; and Joron, J.L.: Quantification of Nb, Ta, Ti and V Anomalies in Magmas Associated with Subduction Zones: Petrogenetic Implications. Earth Planet. Sci. Lett., v. 68, 1984, pp. 297-308.
19. Condie, K.C.; Bobrow, D.J.; and Card, K.D.: Geochemistry of Precambrian Mafic Dykes from the Southern Superior Province of the Canadian Shield. Mafic Dyke Swarms, H.C. Halls and W.F. Fahrig, eds., Geol. Assoc. Canada, Spec. Paper 34, 1987, pp. 95-108.
20. James Beard, unpublished experimental data, 1988.
21. Glikson, A.Y.; Jahn, B.M.: REE and LIL Elements, Eastern Kaapvaal Shield, South Africa: Evidence of Crustal Evolution by 3-stage Melting. Evolution of Archean Supracrustal Sequences, L.D. Ayres, P.C. Thurston, K.D. Card and W. Weber, eds., Geol. Assoc. Canada Spec. Paper 28, 1985, pp. 303-324.
22. Wood, D.A.: The Application of a Th-Hf-Ta Diagram to Problems of Tectonomagmatic Classification and to Establishing the Nature of Crustal Contamination of Basaltic Lavas of the British Tertiary Volcanic Province. Earth Planet. Sci. Lett., v. 50, 1980, pp. 11-30.
23. Menzies, M.A.; Leeman, W.P.; and Hawkesworth, C.J.: Geochemical and Isotopic Evidence for the Origin of Continental Flood Basalts with Particular Reference to the Snake River Plain Idaho, U.S.A. Phil. Trans. R. Soc. Lond. A. v. 310, 1984, pp. 643-660.
24. Shirey, S.B.; and Hanson, G.N.: Mantle Heterogeneity and Crustal Recycling in Archean Granite-Greenstone Belts: Evidence from Nd Isotopes and Trace Elements in the Rainy Lake Area, Superior Province, Ontario, Canada. Geochim. Cosmochim. Acta, v. 50, 1986, pp. 2631-2651.

25. Machado, N.; Brooks, C.; and Hart, S.R.: Determination of Initial 87Sr/86Sr and 143Nd/144Nd in Primary Minerals from Mafic and Ultramafic Rocks: Experimental Procedure and Implications for the Isotopic Characteristics of the Archean Mantle under the Abitibi Greenstone Belt, Canada. Geochim. Cosmochim. Acta, v. 50, 1986, pp. 2335-2348.
26. Cattel, A.: Enriched Komatiitic Basalts from Newton Township, Ontario: Their Genesis by Crustal Contamination of Depleted Komatiite Magma. Geol. Mag. v. 124, 1987, pp. 303-309.
27. Ellam, R.M.; and Hawkesworth, C.J.: Elemental and Isotopic Variations in Subduction Related Basalts: Evidence for a Three Component Model. Contrib. Mineral. Petrol., v. 98, 1988, pp. 72-80.
28. Arculus, R.J.: The Significance of Source Versus Process in the Tectonic Controls of Magma Genesis. J. Vol. Geotherm. Res., v. 32, 1987, pp. 1-12.
29. Neal, C.R.: The Origin and Composition of Metasomatic Fluids and Amphiboles Beneath Malaita, Solomon Islands. J. Petrol. v. 29, 1988, pp. 149-179.
30. Gariepy, C.; and Allegre, C.J.: The Lead Geochemistry and Geochronology of Late-Kinematic Intrusives from the Abitibi Greenstone Belt, and the Implications for Late Archaean Crustal Evolution. Geochim. Cosmochim. Acta, v. 49, 1985, pp. 2371-2383.